Results of the STRV-2 lasercom terminal evaluation tests

A. Biswas, G. Williams, K. E. Wilson,

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak grove Drive, Pasadena, CA

H. Hakakha, R. Steiger, E. Korevaar

AstroTerra Corporation, Sorrento Valley road, San Diego, CA

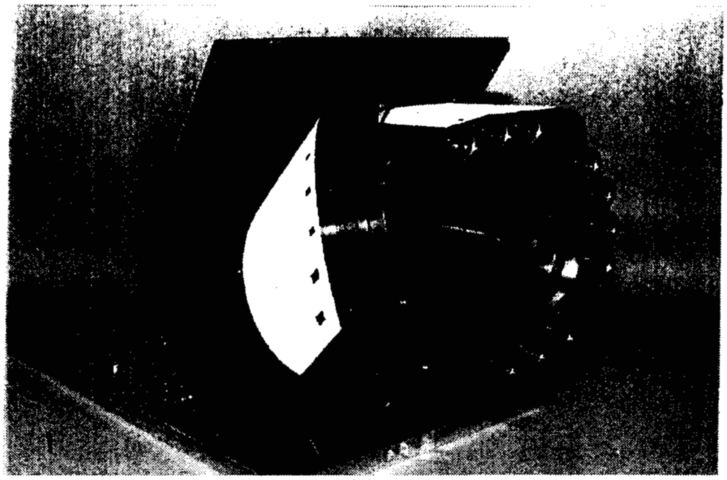
ABSTRACT

The STRV-2 lasercom terminal (LCT) was designed and developed by AstroTerra Corporation of San Diego, California, under funding from the Ballistic Missile Defense Organization (BMDO). Scheduled for launch in late 1998 it will be used to demonstrate, for the first time, high data rate bi-directional satellite-to-ground optical communications. Concurrently with the development of the STRV-2 lasercom NASA/JPL was assembling the lasercom test and evaluation station (LTES), a high quality test platform for pre-flight characterization of optical communications terminals. The respective development schedules allowed evaluation of the STRV-2 LCT using LTES, for a month, prior to integration of the LCT with the spacecraft palette. Final co-alignment of the transmitter lasers to within +/-20 μrads with respect to the receive axis was achieved. This in turn allowed the specified 76 μrad transmit beam divergence to be realized. However, subjecting the LCT to expected on-orbit temperatures revealed that the co-alignment deteriorated causing beam spreading, a finding which prompted the recommendation to operate the lasers warmed up during ground encounters. The "bent-pipe" operation bit-error rates (BER) at 155, 194 and 325 Mbps were ≤ 1E-10 over a ~20 dB range of irradiance measured at the receive telescope aperture. At 500 Mbps BER's of 1E-6 were achieved over a ~6 dB irradiance range, suggesting greater vulnerability to atmosphere induced fades. A pointing offset between the acquisition receivers and transmitter lasers of 1 mrad was measured. The impact of this offset will be to limit acquisition camera framing rates to 87 and 251 Hz, thus limiting the tracking loop bandwidth. Tracking performance tests of the lasercom terminal, though planned, could not be carried out because the software was not ready at the time of testing with LTES. The test results obtained for STRV-2 lasercom terminal will be used for designing the ground receiver.

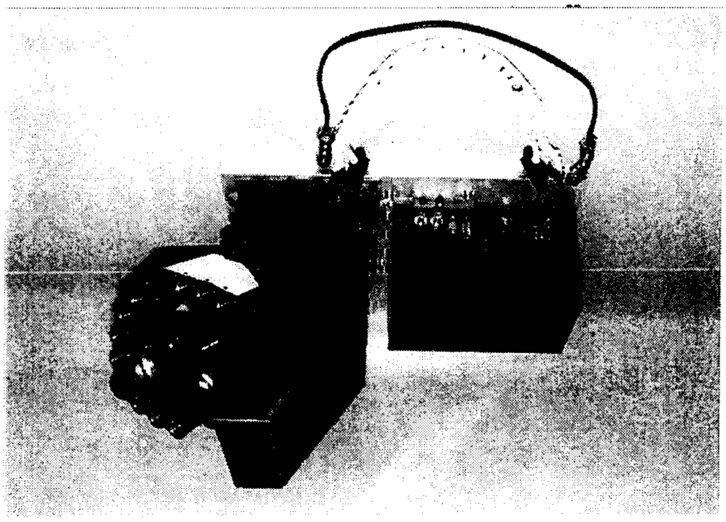
Keywords: STRV-2, free space optical communications, lasercom testing and evaluation

1. INTRODUCTION

The lasercom terminal[1,2] on STRV-2 was designed and developed by AstroTerra Corporation of San Diego, California, under funding from Ballistic Missile Defense Organization (BMDO). STRV-2 is scheduled for launch in late 1998 and the primary objective of the lasercom experiment is to demonstrate, for the first time, high data rate bi-directional satellite-to-ground optical communications. Accurate co-alignment and characterization of the lasercom communications terminal (LCT) performance required a high precision test bed such as the lasercom test and evaluation station[3,4] (LTES) designed and assembled by NASA/JPL. With this in mind and prior to integration with the spacecraft palette, the STRV-2 LCT was brought to the LTES laboratory at JPL, to first, co-align the lasercom terminals eight transmitter lasers and then, to evaluate the effect of expected on-orbit temperatures on the transmitted laser far-field divergence. Additionally, characterization tests in order to evaluate the acquisition, receive and transmit functions of the LCT were performed. These include, measuring the field-of views (FOV's) of the communications and acquisition receivers, the optical power of the transmitters, the transmit and receive wavelength



(a)



(b)

Figure 1.1 (a) Showing the STRV-2 LCT and (b) the LCT connected to the flight electronic box.

characteristics and the "bent-pipe" or "loop-back" bit error rate characteristics. Except for the tracking performance of the LCT which could not be performed due to the unavailability of the tracking software at the time of testing, all other functional features were tested and the results will be used in the design of the ground receivers to be used during the STRV-2 lasercom experiment.

A brief description of the lasercom terminal (LCT) is provided in what follows, for a more detailed description see references 1 and 2. Figure 1.1a shows a photograph of the LCT where the central 14 cm telescope aperture with 5.7 cm obscuration serves as the receive aperture for the two communications channels and the primary acquisition channel. Arranged around this telescope along an approximate semicircular circumference (17.3 cm in diameter) are shown ten 16 mm diameter lasers of which the two at the extremities are cw beacon lasers (852 nm) and the remaining eight are transmitter lasers (810 nm). Also shown along this semicircle are two larger (3.8 cm diameter) apertures, one of which serves as a secondary acquisition channel, the other remaining unused.

The communications receiver channel detectors are avalanche photodiodes (APD's) each of which is designed to accept either right hand circular polarized (RHCP) or left hand circular polarized (LHCP) laser light at 810 nm with a 9 nm bandpass. The primary acquisition detector is a CCD camera behind a Cs atomic line filter (ALF) designed to accept 852.112 nm light with a bandpass of 0.02 nm. The secondary acquisition channel also consists of a CCD detector behind a 4 nm bandpass filter centered at 852 nm. Each of the transmitter lasers emits a 16 mm diameter beam. The front end optics of these transmitters are designed so that a bank of four lasers each, emit RHCP or LHCP light. The LCT is mounted on a two axis (slant and azimuth) precision gimbal. Figure 1.1b shows the LCT connected to the flight electronic box, which provides the control interface to all the gimbal motors, detectors, lasers and health monitors on the terminal.

A detailed description of LTES appears in references 3 and 4 and will not be repeated here, however, for the sake of completeness an optical layout diagram is shown in Figure 1.2. Modifications to LTES were necessary in order to transmit the appropriate beacon to the STRV-2 LCT, namely, a 810 nm modulated LHCP or RHCP beam for the communications receivers and a cw tunable 852 nm RHCP beam for the acquisition receivers. Moreover the data channel of LTES was also modified to accept either RHCP or LHCP laser light.

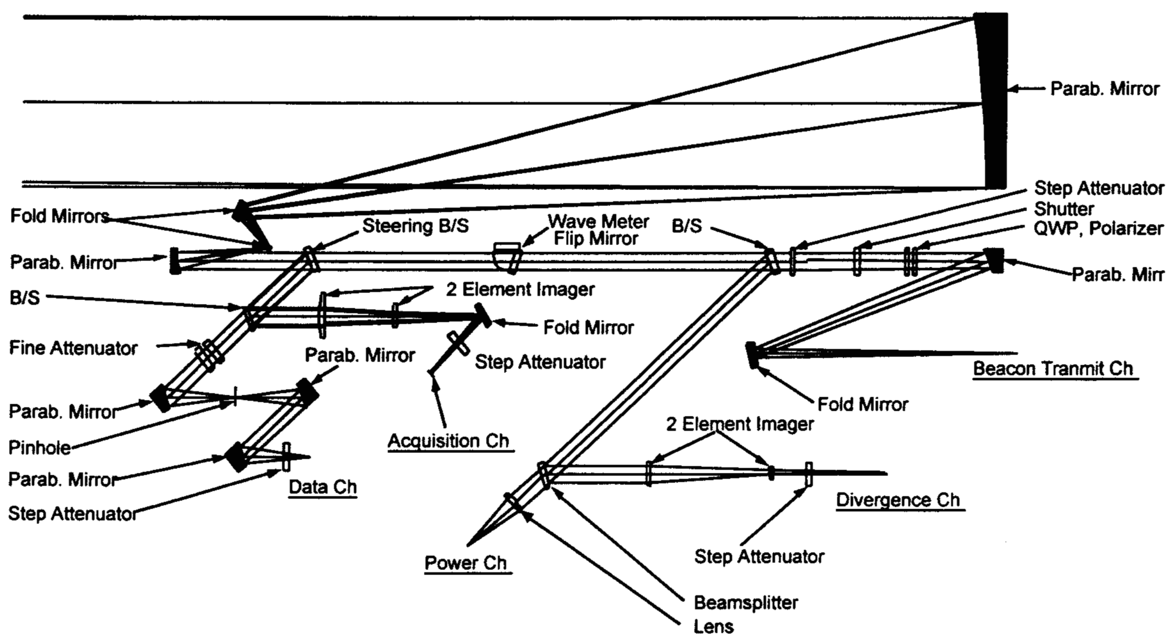


Figure 1.2 Showing the optical layout of LTES which was used as a test bed for characterizing the STRV-2 LCT.

2.0 TEST SETUP

Figure 2.1 is a schematic diagram of the experimental set up used to characterize the LCT. The glove box enclosure was mounted on a base plate and then bolted to a sturdy three point laboratory stand that allowed height adjustment. The glove box enclosure was continuously purged with extra dry nitrogen (~5-10 standard cubic foot per hour) during the experiment, in order to maintain a relative humidity (RH) of <10%. The low RH kept the LCT in a controlled environment, and limited the moisture absorbed into the LCT's composite material. Water absorption could degrade the stability of the LCT's structure and hence the terminal's performance. The flowing dry nitrogen, after pre-cooling by flowing through a liquid

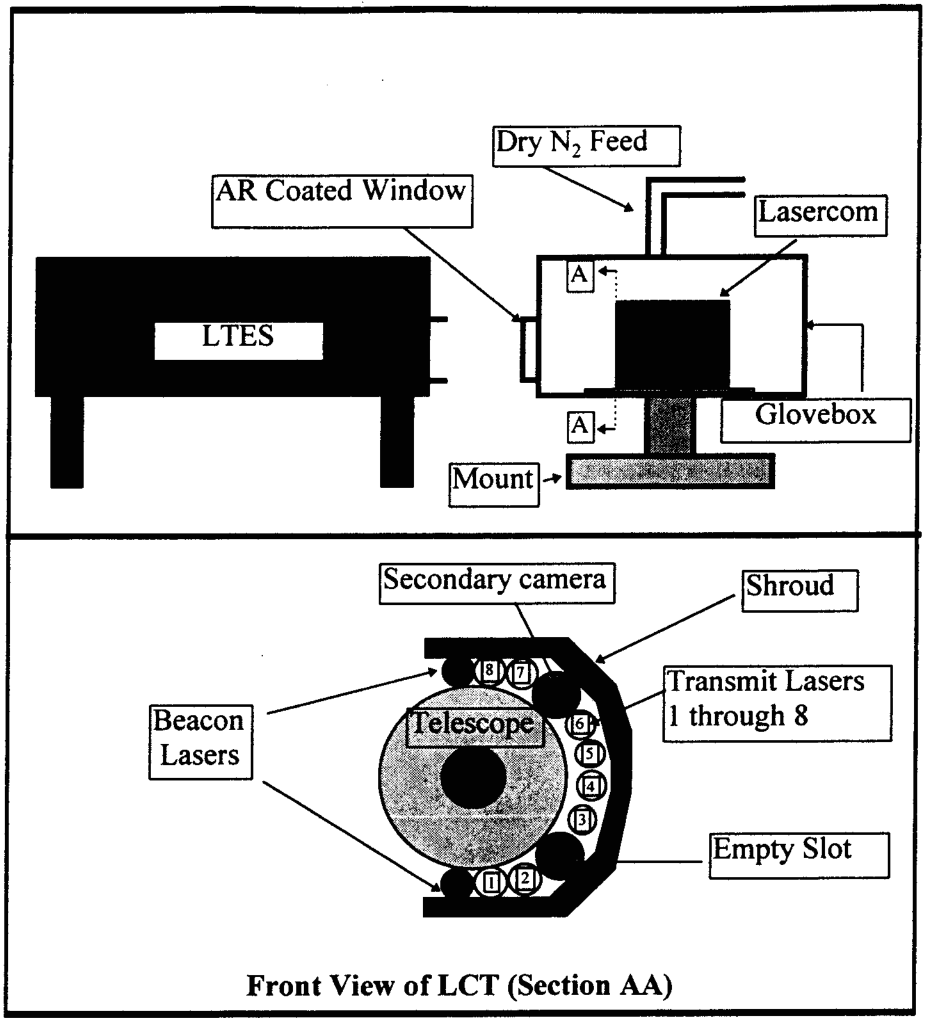


Figure 2.1 A schematic view of the test setup used to perform characterization of STRV-2 LCT using LTES.

nitrogen dewar, was used to cool the LCT during tests to evaluate the effect of temperature on the transmitter laser co-alignment.

An electrical feed-through in the glove box connected the LCT to the flight electronics box which was interfaced to the satellite control monitor (SCM) simulator computer. Software resident in this computer allowed command, control and data acquisition from the LCT.

The entire LCT assembly was positioned in front of and facing the LTES aperture. Coarse horizontal and vertical adjustment of the assembly were used to achieve nominal co-alignment of the respective receive/transmit axes of the LCT and LTES. Fine adjustments were then made by controlling the slant and azimuth pointing of the LCT by issuing commands via the SCM computer.

3.1 CO-ALIGNMENT OF TRANSMIT LASERS

The center of the field-of-view (FOV) of the communications or APD receivers is taken as the receive axis of the LCT. In order to locate this center, a beacon[4] was transmitted from LTES to the LCT. The beacon beam was at 810+/-4 nm and modulated (155 Mbps) with a pseudo-random bit sequence (PRBS) non-return to zero (NRZ) PN7 data stream. The polarization state of the beacon beam was either RHCP or LHCP. Of the two communications receivers on the LCT, APD#1 accepts RHCP light and its output after amplification on the LCT, modulates transmit lasers numbered 3, 4, 5 and 6, which in turn, emit RHCP light. Similarly, APD#2 accepts LHCP laser light transmitted from LTES and its output is used for modulating lasers 1, 2, 7 and 8 which emit LHCP light. In other words, the laser signal transmitted from LTES is received and regenerated on the LCT and transmitted back to LTES. This is the "bent-pipe" or "loop-back" mode of operation. The data channel on LTES is configured to accept either RHCP or LHCP light, corresponding to whatever polarization state is being transmitted from LTES. The LTES data detector senses the returned light from the LCT and displays its output on a digital oscilloscope. The upper trace of Figure 3.1 shows the data stream used to modulate the beacon laser on LTES while the lower trace shows the LTES data channel signal. An examination of Figure 3.1 indicates a ~ 100 ns delay between the LTES transmitted and received signal which accounts for the optical round trip and electronic transit delays. Once the oscilloscope display shown in Figure 3.1 is obtained, stepped scans of the LCT slant and azimuth directions are initiated. For scans in both directions the motor encoder positions, where degradation of return signal is encountered, are noted and these positions demarcate the extremities of the APD FOV. Such scans were performed for both the APD receivers. By interpolating between the extremities the respective center of FOV's for each APD receiver was established. The repeatability of these scans was +/- 10 µrad. Table 3.1 below shows the measured FOV's in azimuth and slant units, as well as, transformed horizontal and vertical units.

The respective FOV centers, of each APD detector, were offset by 200 x 100 µrad (slant x azimuth) or 130 x 30 µrad (horizontal x vertical). A check of the motor encoder readings was performed by moving the LCT from one APD center to the other and simultaneously recording the motion of the transmitted laser spot centroid on the LTES acquisition detector. The centroid moved by 134 x 22 µrad showing a good agreement with the motor encoder readings.

Table 3.1 Showing the measured FOV's for each of the APD receivers on the LCT

	FOV from motor encoder position Azimuth x Slant (µrad)	FOV obtained by transforming the azimuth x slant to horizontal x vertical (µrad)
APD #1 (RHCP)	1100 x 1100	700 x 600
APD #2 (LHCP)	1300 x1400	830 x 780

The receive axis FOV center is taken as the gimbal motor encoder positions corresponding to a location interpolated between the two APD detector centers.

With the LCT commanded to slant and azimuth positions corresponding to the located APD center, Figure 3.2 shows schematically the arrangement for referencing this position on the LTES divergence channel detector. The solid lines indicate the beacon transmitted from LTES to the LCT while the dashed lines correspond to the path of retro-reflected portions of this beacon re-directed to the LTES divergence channel. Since the beacon is well collimated the retro-reflected spots from the two retro-reflectors converge on the divergence detector. The centroid of this spot serves as a reference for the LCT receive axis center. The transmitted laser beam path from the LCT to the divergence channel is indicated by the dotted lines. Each of the transmitter laser spots must be brought to co-incidence with the reference spot on the divergence CCD camera in order to co-align the eight transmitter lasers to the receive axis and to each

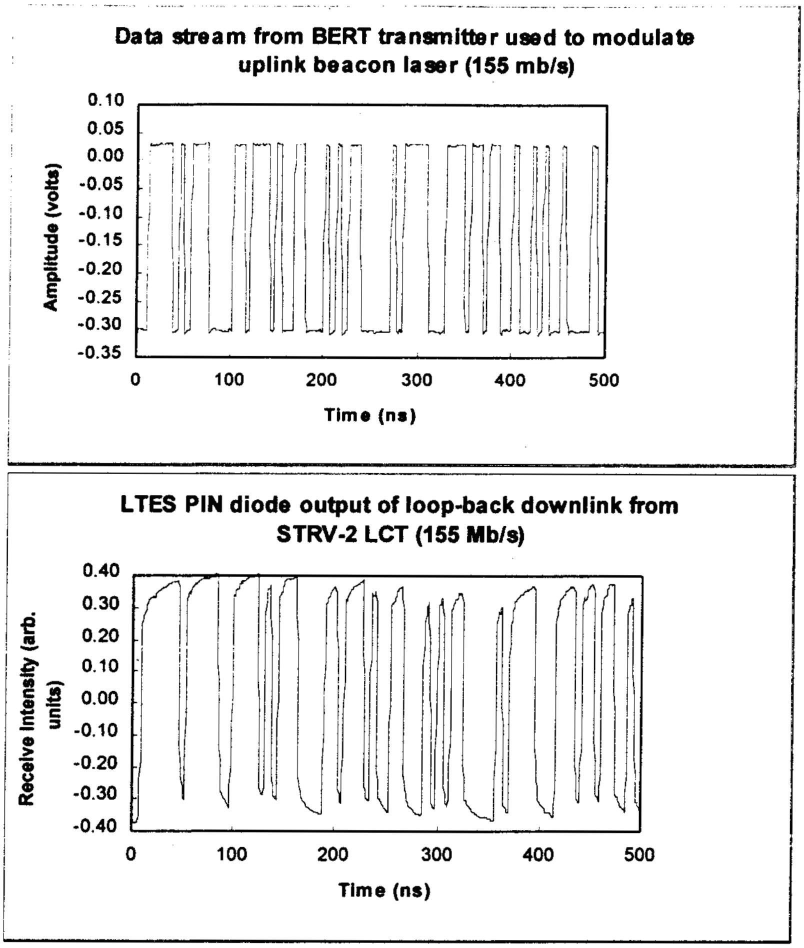


Figure 3.1 Showing the data stream used to modulate the LTES beacon laser which is transmitted to the LCT and the resulting laser signal transmitted by the LCT in the bent-pipe mode. The lower trace is contributed by a bank of four of the eight transmit lasers and is delayed due to optic round-trip and electronic transit time by 100 ns.

other. This was done by manually adjusting a steering lens in front of each laser transmitter. The spots could be brought to within +/- 20 μrad of this reference position. After 24 hours of the initial alignment no significant mechanical relaxation was apparent and the steering lenses were glued down with epoxy.

3.2 TEMPERTURE SENSITIVITY OF TRANSMIT LASER CO-ALIGNMENT

The co-alignment of the transmitter lasers on the STRV-2 LCT was achieved at laboratory ambient temperature after the lasers had warmed up. This corresponded to a temperature of 30+/-2 °C sensed by the temperature sensors on the shroud covering the laser transmitters (see Figure 2.1). Planned operational scenarios call for this temperature to be ~ 0°C. The sensitivity of the transmit laser co-alignment at the expected on-orbit temperature was investigated. The LCT was cooled while the combined laser spot (all eight transmit lasers turned on) divergence was monitored using the LTES divergence channel. Figure 3.3 shows contour plots of the combined laser spot at 0, 11, 20 and 32°C. The beam divergence of the individual laser spots (not shown) are unaffected by the temperature change. As shown the divergence of the combined laser spot, however, increases significantly with lowering of temperature. This is due to thermal drift. A simulation, assuming Gaussian profiles for each transmit laser predicts the loss of on-axis power in dB as indicated in Figure 3.3.

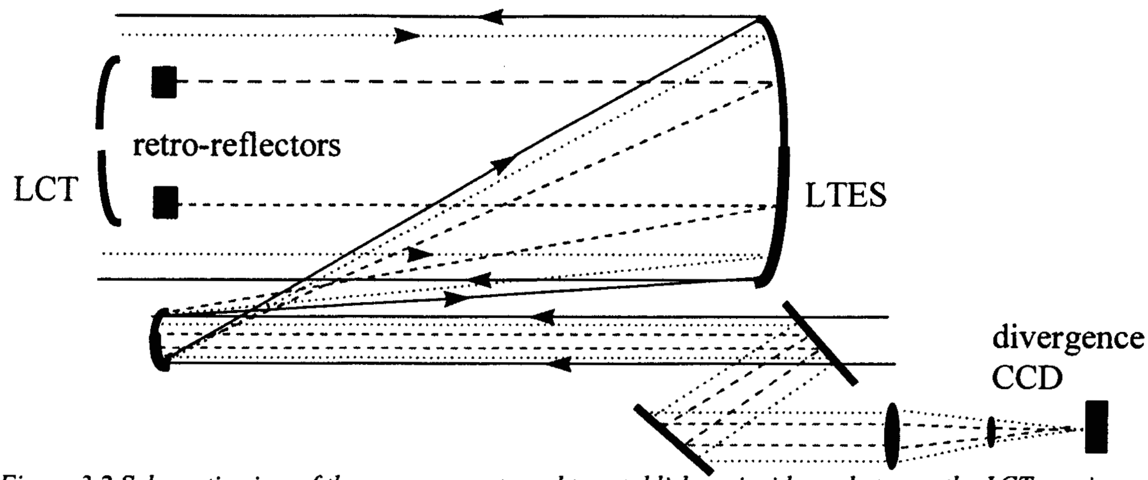


Figure 3.2 Schematic view of the arrangement used to establish co-incidence between the LCT receive axis and the transmit lasers on the LCT.

The results depicted in Figure 3.3 show that at the planned operating temperature of 0°C the beam divergence far exceeds the design divergence of 72 μrad with a corresponding lowering of on-axis power. Based on these findings we recommend that the lasers be heated up to 30°C in space. Heaters for accomplishing this are available on the terminal.

3.3 TRANSMIT LASER POWER AND WAVLENGTH

Table 3.2 shows the power measured for the transmitter and beacon lasers on the STRV-2 LCT, where L1, L2....L8 represent the transmitter lasers and B1, B2 denote the beacon lasers. The powers were measured at each laser aperture. At lower temperatures an increase in power is observed. However, the loss in on-axis power due to beam spreading upon cooling of the LCT, just discussed in section 3.2, far outweighs this modest increase.

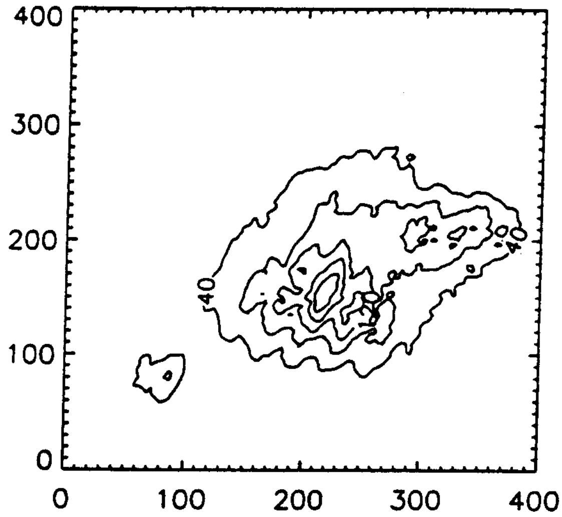
Figure 3.4 shows the LCT wavelength measured with all eight transmitter lasers turned on, at two different temperatures. The wavelength was measured using a scanning monochromator. As expected for AlGaAs lasers there is a decrease in wavelength at lower temperatures.

Table 3.2 Power measurements (mW) made on STRV-2 LCT transmit lasers modulated at 155 Mb/s and beacon lasers operating CW

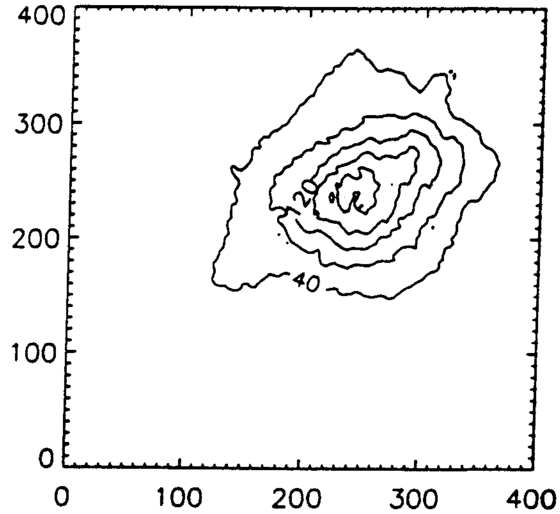
	L1	L2	L3	L4	L5	L6	L7	L8	B1	B2
30°C Coherent Fieldmaster P/N 0210-761-99 SN# B888	32	39	33	29	37	39	29	39	-	-
30°C Scientech 362 Model 38-0101 S/N 2531	32	40	34	29	37	39	30	40	67	61
7°C Scientech 362 Model 38-0101 S/N 2531	35	44	42	36	45	43	36	42	66	68

3.4 BENT-PIPE SENSITIVITY

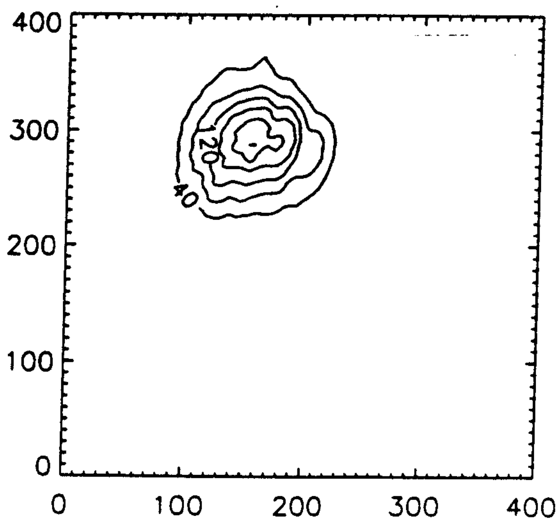
The bent-pipe operation already described in section 3.1 was characterized in terms of the bit-error rate (BER) performance. The LTES data channel output was used to record BER while beacon power transmitted from LTES was varied by using variable attenuation. Figure 3.5 shows the BER characteristics



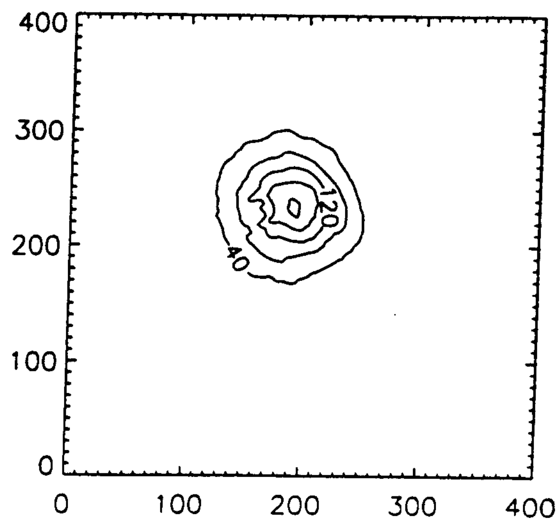
(a)
T = 0°C
$FWHM_x$ = 119μrad, $FWHM_y$ = 185μrad
On-axis Power Loss = -5.2 dB



(b)
T = 11°C
$FWHM_x$ = 127μrad, $FWHM_y$ = 111μrad
On Axis Power Loss = -4 dB

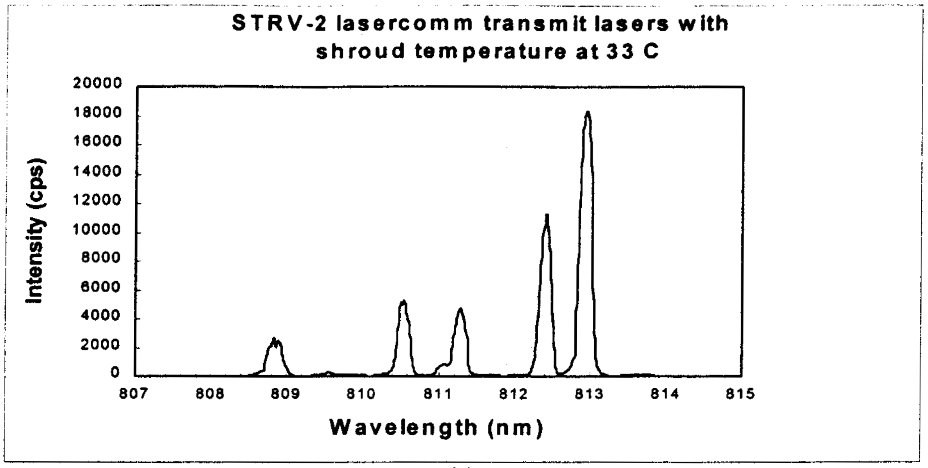


(c)
T = 20°C
$FWHM_x$ = 85μrad, $FWHM_y$ = 81μrad
On-axis Power Loss = -1.8 dB

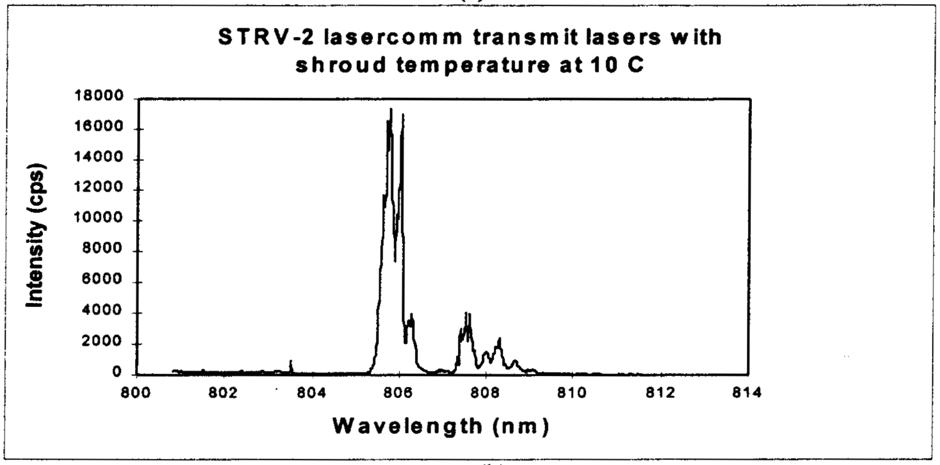


(d)
T = 32°C
$FWHM_x$ = 76μrad, $FWHM_y$ = 79μrad
On Axis Power Loss = -0.5 dB

Figure 3.3. The laser spot transmitted from STRV-2 lasercom and incident on the LTES divergence detector at (a) 0°C (b) 11°C (c) 20°C and (d) 32°C. The divergence in the x- and y- directions are shown. The estimated loss in on-axis power relative to perfectly co-aligned lasers is indicated.



(a)



(b)

Figure 3.4 Transmit laser wavelengths at two different temperatures

for PN7 modulation at a number of different data rates ranging from 155 to 500 Mbps. The BER characteristics shown were representative of the LCT's bent-pipe performance and not of the system being used for measurement. This was tested by transmitting the LTES beacon directly to the data channel detector at comparable power levels and verifying zero errors.

In Figure 3.5, the irradiances along the abscissa, correspond to values calculated to be incident at the LCT telescope aperture. The calculation was based on the measured power distribution incident upon the LCT receive aperture and taking into account the obscuration. The irradiance levels reported are reliable to within a factor 1.7. The deterioration of BER at the higher irradiances occur because of detector saturation. For data rates of 155, 194 and 325 a robust link with BER's of at least 1E-10 were obtained at beacon irradiance levels ~1-100 nW/cm^2. However, at 500 Mbps a 1E-6 BER can be obtained only over a much narrower irradiance range of 10-40 nW/cm^2. This data suggests that robust links for bent-pipe operation should be achievable at the lower three data rates. At 500 Mbps good performance (BER of 1E-6) can be expected, however, the link may be vulnerable to atmospheric fades since a narrower dynamic range of operation is indicated.

3.5 ACQUISITION RECEIVER CHARACTERIZATION

The acquisition receivers are 384 x 288 pixel, charge coupled detectors (CCD) with 23 micrometer pixel pitch (70 μrad/pixel). The measured transmission characteristics of the filters in front of each of the receivers is shown in Figure 3.6. They were mapped by transmitting a cw RHCP 852 nm beacon from

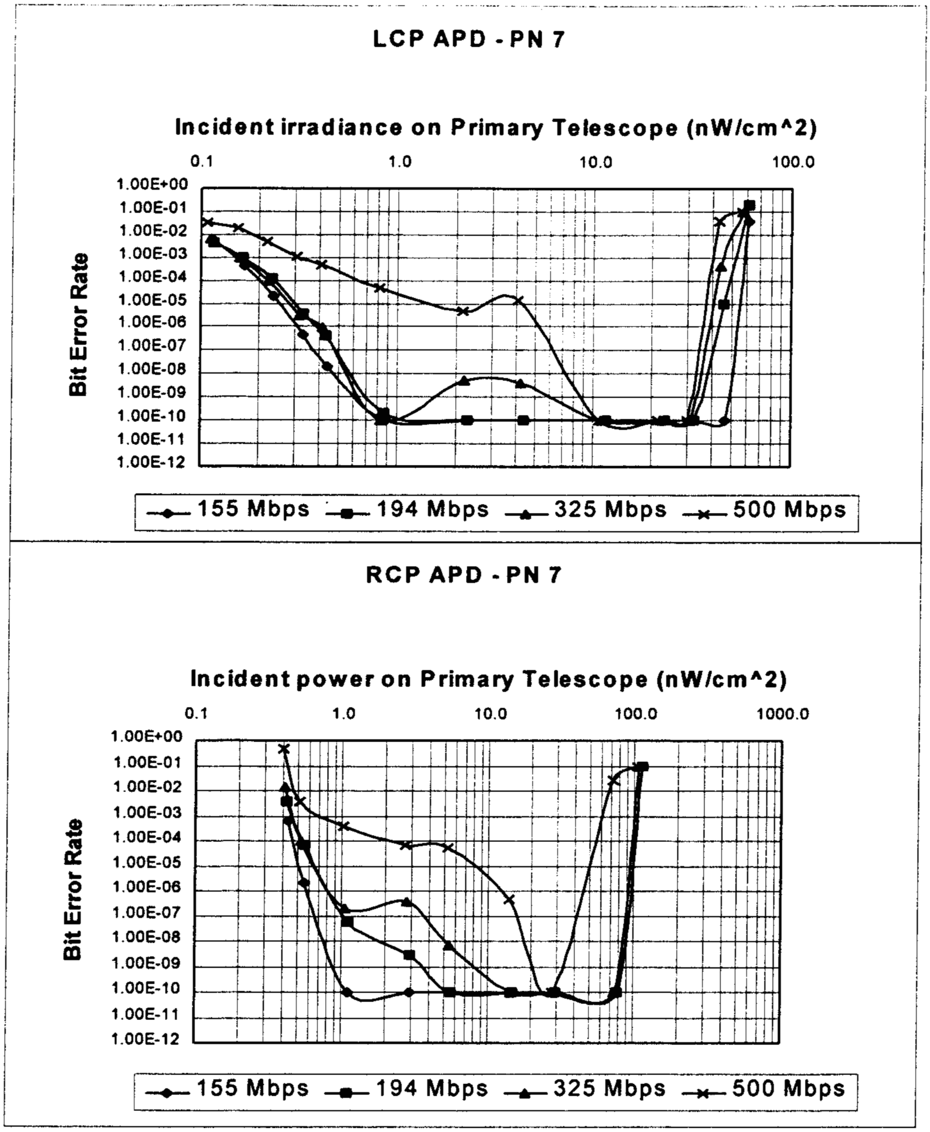
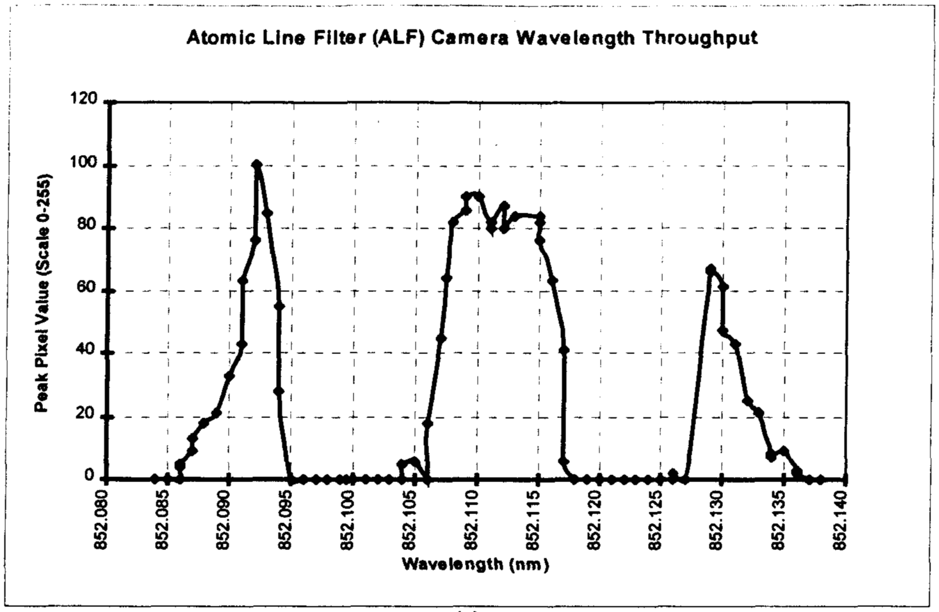


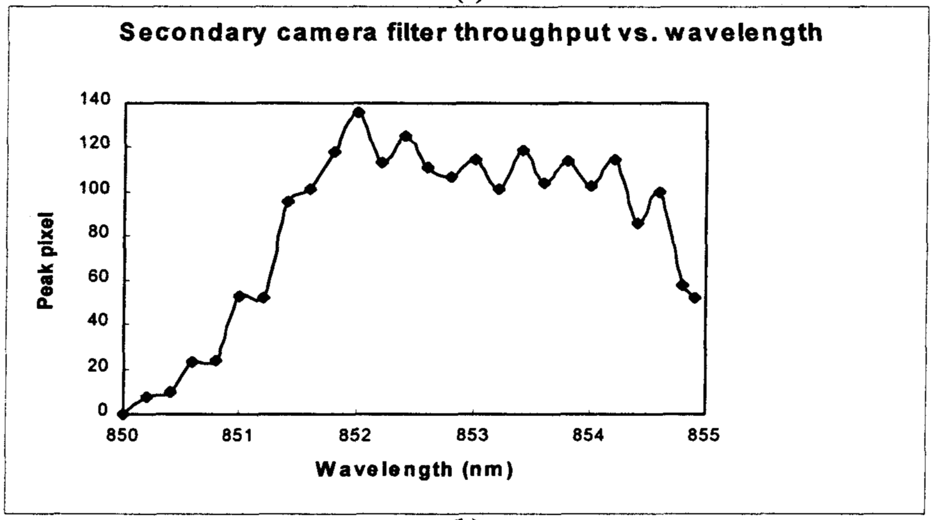
Figure 3.5 BER characteristics as a function of irradiance incident on the telescope aperture of the LCT.

LTES to the LCT. The 852 nm laser used was a New Focus Series 6200 extra-cavity tunable diode laser which could be tuned in steps of 0.007 nm. The LTES wavemeter was used to independently monitor wavelength being transmitted to the LCT. The fine resolution provided by the tunable diode laser was necessary for mapping out the transmission of the Cs ALF in front of the primary acquisition receiver. The ALF is heated and maintained ~122°C by software. During testing the LCT at JPL, the control software worked intermittently causing fluctuations in the ALF temperature. This problem probably caused the lack of smoothness of the measured filter transmission profile. AstroTerra Corporation has reported that the software problem was fixed during post integration tests.

Other characteristics measured for the acquisition receivers, namely, field-of view, offset with respect to APD center (transmit axis), acquired spot size and sensitivity are shown in Table 3.3. Of these the offset with respect to the transmit axis is most significant from an operational standpoint. The originally designed camera frame rates were 87, 251, 677 and 1451 Hz.



(a)



(b)

Figure 3.6 Filter transmission for (a) primary acquisition camera and (b) secondary acquisition camera

Table 3.3. Showing some measured characteristics for the acquisition detectors on the STRV-2 LCT.

	FOV (mrad)	Offset wrt APD center	Spot Size (μrad)	Sensitivity (pW/cm^2)
Primary Acquisition Camera (14 cm aperture with 5.7 cm obscuration)	39 x 28	414 x 840 μrad	~100 +/- 30	0.76 (G=0) @ 87 Hz 0.36 (G=32) @ 87 Hz 0.13 (G=64) @ 87 Hz 3.7 (G=0) @ 251 Hz 0.94 (G=32) @ 251 Hz 0.71 (G=64) @ 251 Hz
Secondary Acquisition Camera (3.8 cm aperture)	30 x 33	1 mrad	~100 +/- 30	~10 (G=0) @ 87 Hz 3.3 (G=255) @ 87 Hz 14.1 (G=255) @ 251 Hz

At the higher readout rates the camera FOV's shrink in one dimension with the active region confined near the center of the camera. The ~ 1 mrad offset with respect to the transmit axis implies that at the two higher frame rates the centroid of the acquired beacon laser spot will be outside the active region when the LCT is pointed correctly to the ground receivers. Thus tracking operations using the higher acquisition frame rates may not be possible. The impact of this limitation is unknown at this point since no information on spacecraft jitter is available.

4.0 CONCLUSION

In conclusion, we used the JPL developed LTES facility to co-align and evaluate performance of the STRV-2 LCT built by AstroTerra Corporation. We achieved transmitter laser co-alignment, measurement of transmitted laser divergence and its temperature sensitivity, transmitter laser power and wavelength measurement, bent-pipe operation BER characteristics and acquisition detector characterization. The results will be used to design the ground station for the planned satellite-to-ground optical communication demonstration. The main findings led to a recommendation for operating the transmitter lasers at a shroud temperature of 30°C in contrast to the originally planned 0°C operation. The bent pipe sensitivity tests indicate a 20 dB irradiance range at the receiving telescope aperture over which BER's of ≤1E-10 can be achieved at 155, 194 and 325 Mbps, while at 500 Mbps this range drops to ~6 dB for a 1E-6 BER. Because of a 1mrad offset between the acquisition FOV center and the transmit axis, tracking loop bandwidth will be limited by the maximum acquisition camera frame rate of 251 Hz. Finally, tracking tests could not be performed due to unavailability of software at the time of testing.

4. ACKNOWLEDGMENTS

We would like to acknowledge the guidance provided by Dr. K. Wu of BMDO and Dr. Ranty Liang and Dr. James Lesh of JPL. The technical assistance of Norm. A. Page, David Erickson, and F. Razo of JPL during various phases of the testing are gratefully acknowledged.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. It was also supported by AstroTerra Corporation under contract to the Ballistic Missile Defense Organization.

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